Estimation errors of single dipole model applied to twin dipole activity: Computer simulation study

T. Imada[1,2], T. Mashiko[1,2], and H. Sekine[3]

[1]*NTT Communication Science Laboratories, Nippon Telegraph and Telephone Corporation, 243-0198 Atsugi, Japan;* [2]*Real World Computing Partnership, 243-0198 Atsugi, Japan;* [3]*NTT Advanced Technology, 243-0198 Atsugi, Japan*

1 Introduction

Various methods have been proposed to solve magnetoencephalographic inverse problems although the problem itself is ill-posed and in principle infinite number of solutions are possible. Among them, the simplest method is the single dipole in a spherical head model, which has been practically used in a lot of papers to get the dipoles activated by the sensory and cognitive tasks. However, if the number of active locations in the brain is more than one, for example two closely located dipoles, this simplest single dipole solution brings an error in location and moment. This error seems to be larger when the distance of the two dipoles is smaller, when the dipole current orientations are parallel or antiparallel, and when the dipole current strengths are equal. Lütkenhöner discussed the separability of two dipoles [1]. In his paper, by simulating localization of a single dipole from the magnetic fields produced by two dipoles with various relationships including the distances and moments, he showed the separability of two dipoles in terms of necessity of introducing multiple dipole solution. In his simulation, he employed all channels of the 296-channel planar type whole-head virtual measurement system to localize a single dipole from the magnetic fields produced by two dipoles. However, if we localize a single dipole using several local channels of a whole-head measurement system that detected the magnetic fields produced by two dipoles, we are able to localize two separated dipoles under some conditions, namely when the two dipoles have some relationships of distance and moment. This is often observed when localizing the auditory N100m dipoles in the left and right hemispheres. Moreover, this localization with several locally selected channels is employed in most of experiments using a partial-head measurement system. Those who are using the partial-head measurement system to record the magnetic fields are implicitly selecting the local channels when they place the channel array over some part of the head for the measurement. When localizing multiple dipole activity by a single dipole method, this local-channel selection method has an advantage over the all-channel selection method. We can get more precise localization of the first dipole by selecting local channels that receive stronger magnetic signals from the first dipole and weaker signals from the second dipole as shown in Fig. 1.

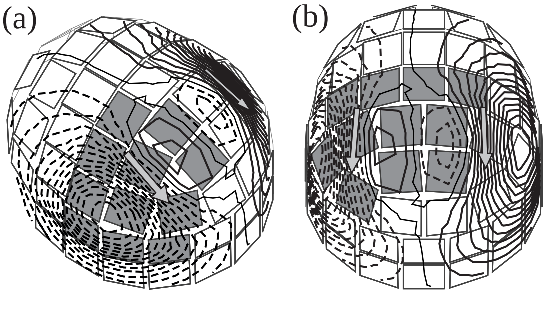

Figure 1**:** *Local-channel selection method. Arrow indicates an assumed dipole.*
a) Channel selection (shaded) for better estimation
b) Channel selection (shaded) for worse estimation

In this paper, we calculated the estimation errors of position and moment of the dipole localized by this single dipole method using locally selected channels rather than all channels of the whole-head measurement system.

2 Methods

2.1 Original dipole parameters

We assumed the following 52 dipoles for the simulation.

1. dipole locations
   - a. Fourteen single dipoles at the depth of 10 mm, making 7 pairs of dipoles with the distance of 20, 30, 40, 50, 60, 70, and 80 mm
   - b. Fourteen single dipoles at the depth of 20 mm, making 7 pairs of dipoles with the distance of 20, 30, 40, 50, 60, 70, and 80 mm
   - c. Fourteen single dipoles at the depth of 30 mm, making 7 pairs of dipoles with the distance of 20, 30, 40, 50, 60, 70, and 80 mm

d. Ten single dipoles at the depth of 40 mm, making 5 pairs of dipoles with the distance of 20, 30, 40, 50, and 60 mm

Any of the above dipole pairs include one dipole in the left hemisphere and the other in the right.

2. current strength: 10, 20, 30, 40, and 50 nAm (see waveforms in Fig. 2)
3. the relationship of current orientations between the paired dipoles: parallel, perpendicular, and antiparallel
4. without noise and with 10-fT/cm Gaussian noise

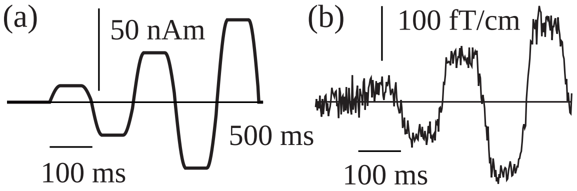

Figure 2**:** *Dipole and magnetic waveforms. a) Original dipole waveform b) magnetic waveform from the above dipole with 10-fT/cm Gaussian noise.*

2.2 Magnetic waveform calculation parameters

We employed the following parameters for calculating magnetic field values.

1. sampling frequency = 500 Hz
2. cut-off frequency of low-pass digital filter = 40 Hz (only for noise condition)
3. baseline = from –100 ms to 0 ms

2.3 Simulation procedures

The simulation was done in the following procedure.

step 1: Calculate magnetic fields at Neuromag-122 sensor locations for all of the above dipoles, resulting in 520 simulations for single-dipole activities and 780 simulations for two-dipole activities.

step 2: Select 70 sets of locally selected channels, each covering a part of head.

step 3: Do the following 3 estimations every 2 ms;

a. model “a single dipole in a sphere” for single dipole activities
70 locally selected channel sets produced 3500 ECDs for 100-ms activity.

b. model “a single dipole in a sphere” for two-dipole activities
70 locally selected channel sets produced 3500 ECDs for 100-ms activity.

c. model “two dipoles in a sphere” for two-dipole activities
A set of all channels except for those covering the frontal area produced 100 ECDs for 100-ms activity.

step 4: Select the ECDs satisfying the following criteria;

a. goodness-of-fit value >= 80% (>= 99% for single dipole activities without noise),

b. 95%-confidence-volume value < 2145 mm^3 (an 8-mm radius sphere volume),

and

c. stable active location staying within 4-mm radius sphere for 10 ms or longer while satisfying the above 2 criteria.

The resulted time series of stable ECDs is called an ECD cluster.

step 5: Create an ECD group. In this group, the member is ECD clusters, and any two members are within 16-mm distance. This matches the sphere of 95%-confidence volume.

step 6: Calculate the distance between the group location (an average location of all member ECDs in that group) closest to the original dipole location.

3 Results

3.1 Single dipole activity

When no noise was added to the original magnetic waveform, naturally no error was found in location, current strength, or current orientation. When the 10-fT/cm noise was added, the estimation error was strongly affected by the signal-to-noise ratio (SNR) as expected. Table 1 shows the SNR of various dipole locations (original dipole strength = 40 nAm).

Table 1: *Signal-to-Noise Ratio of a single dipole activity (40 nAm). The value indicates the average SNR of single dipoles selected from a pair of dipoles with distance of 20-30 mm and 40-80 mm (See Section 2.1).*

	Dipole Depth			
Distance	10 mm	20 mm	30 mm	40 mm
20-30 mm	16.11	8.16	4.69	2.76
40-80 mm	17.2	8.69	5.59	3.18

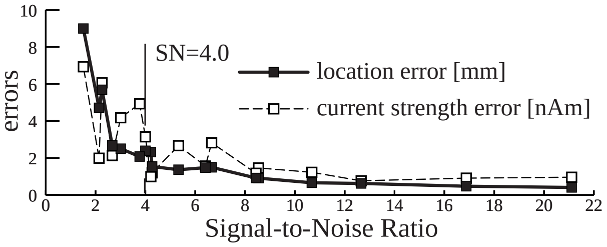

Figure 3**:** *Location and current strength errors vs. Signal-to-Noise Ratio values.*

The estimation error was shown as a function of SNR in Fig. 3. From Fig. 3, it is recommended to use data with SNR of 3 or more to obtain the source localization with less than 3 mm location error. However, as shown in step 4-b in Section 2.3, magnetic data with SNR of 2 or more can be used if we accept the location error of 8 mm. The estimation errors for location, current strength, and current orientation, obtained by steps 2 to 6 in Section 2.3, are shown in Fig. 4.

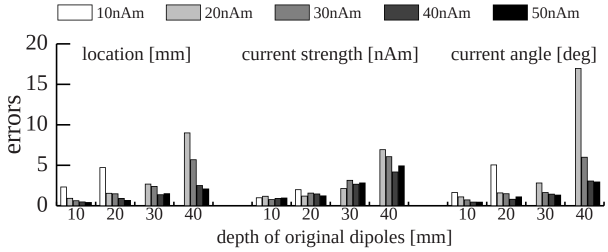

Figure 4**:** *Estimation errors for single dipole activity with 10-fT/cm Gaussian noise.*

It is obvious that location error was less than 3 mm in most of cases when the dipole depth was 30 mm or less. This is easily understood from Table 1 and Fig.3 because the SNR was more than 3 when the dipole depth was 30 mm or less.

3.2 Two dipole activity

Two-dipole activity was analyzed in two ways, as shown in step 3-b and 3-c in Section 2.3.

For the simulation without magnetic noise, the errors of location, current strength, and current orientation are depicted in Fig. 5 for the single dipole model and Fig. 6 for the two-dipole model.

In Figs. 5 and 6, to simplify the results, we averaged errors across dipoles with 20- and 30-mm distances and across those with 40- to 80-mm distances.

In Fig. 5 (single-dipole model), the location error was 6.8 mm in average and about 14 mm at largest. However, the current strength error was 13 nAm in average and about 30 nAm at largest, which corresponds to 75% of the original current strength. The largest current strength error was obtained in the parallel current condition whereas the largest current orientation error was obtained in the perpendicular condition. Note that the current orientation error was very small for the parallel and antiparallel conditions.

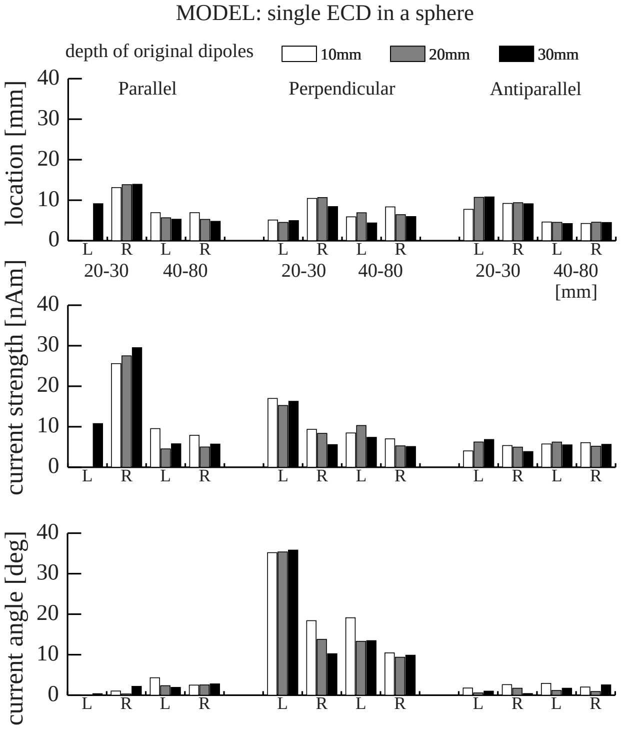

Figure 5**:** *Errors of location (upper), current strength (middle), and current orientation (bottom) for two dipole activity (40 nAm each) without noise, when estimated with the single-dipole model. "20-30" and "40-80" indicate the distance between the paired dipoles. The errors were averaged across 20- and 30-mm distance dipoles, and across 40-, 50-, 60-, 70-, and 80-mm distance dipoles. The left panel illustrates the error for two dipoles with parallel current directions, the middle panel those with perpendicular current directions, and the right panel those with antiparallel current directions. Data are not shown if one of dipoles were not successfully localized. "L" and "R" mean the dipoles in the left and right hemisphere, respectively.*

In Fig. 6 (two-dipole model), the location error was 2.7 mm in average and about 14 mm at largest. However, the current strength error was 8.2 nAm in average and about 29 nAm at largest, which corresponds to 75% of the original current strength.

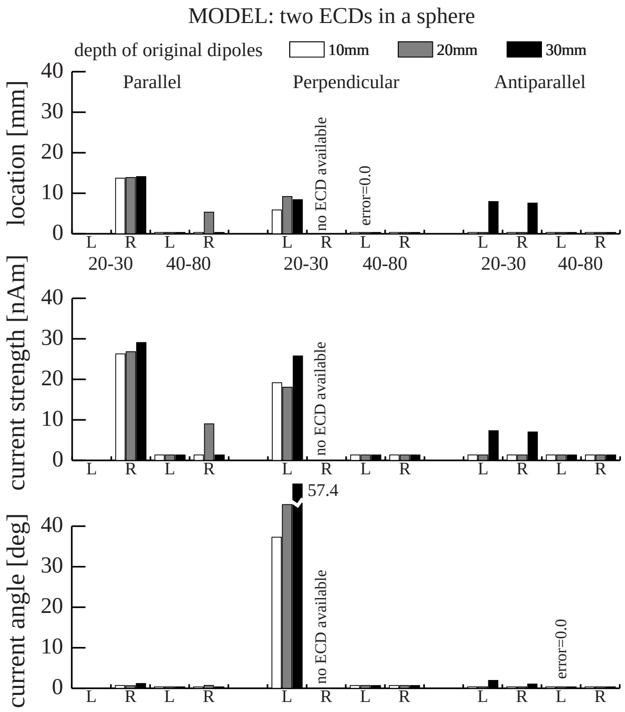

Figure 6: *Errors of location (upper), current strength (middle), and current orientation (bottom) for two-dipole activity (40 nAm each) without noise, when estimated with the two-dipole model. See caption of Fig.5 for further details.*

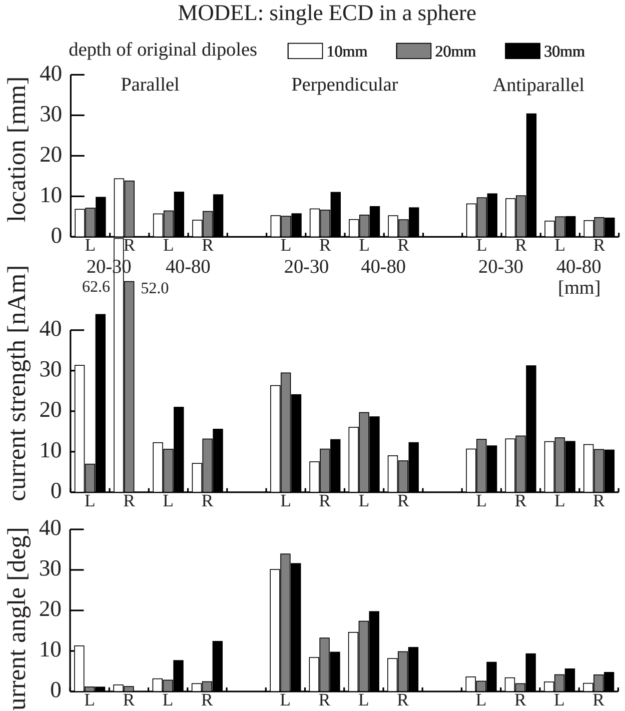

Figure 7: *Errors of location (upper), current strength (middle), and current orientation (bottom) for two-dipole activity (40 nAm each) with 10-fT/cm Gaussian noise, when estimated with the single-dipole model. See caption of Fig.5 for further details.*

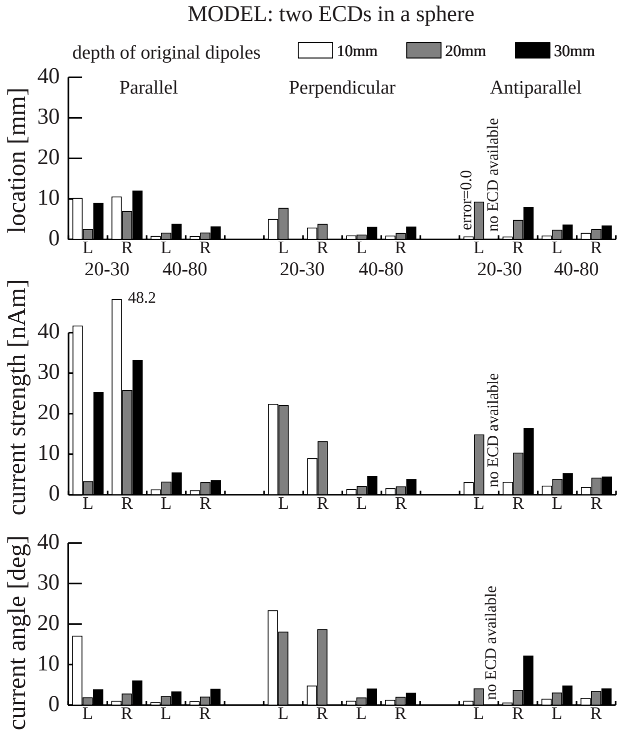

Figure 8: *Errors of location (upper), current strength (middle), and current orientation (bottom) for two-dipole activity (40 nAm each) with 10-fT/cm Gaussian noise, when estimated with the two-dipole model. See caption of Fig.5 for further details.*

Table 2: *Average errors in location, current strength, and current orientation (angle) for the data without noise (top) and with noise (bottom). The symbols ∥, ⊥, and // mean parallel current direction, perpendicular current direction, and antiparallel current direction, respectively.*

no noise	MODEL	∥	⊥	//	**mean**
location	singleECD	7.8	6.6	5.9	6.8
[mm]	twoECDs	5.2	2.2	0.8	2.7
strength	singleECD	17.9	12.9	8.4	13.0
[nAm]	twoECDs	14.6	9.0	1.0	8.2
angle	singleECD	2.2	16.1	1.7	6.7
[deg]	twoECDs	0.2	13.4	0.2	4.6

with noise	MODEL	∥	⊥	//	**mean**
location	singleECD	8.3	6.2	7.1	7.2
[mm]	twoECDs	4.5	3.2	3.6	3.7
strength	singleECD	20.0	14.9	12.1	15.7
[nAm]	twoECDs	11.1	6.4	5.8	7.8
angle	singleECD	4.3	16.0	3.8	8.0
[deg]	twoECDs	3.8	6.5	4.6	5.0

For the magnetic data with 10-fT/cm Gaussian noise added, Figs. 7 and 8 correspond to Figs. 5 and 6, respectively. In Fig. 7 (single-dipole model), the location error was 7.2 mm in average and about 14 mm at largest (exceptionally large error 30 mm was excluded). However, the current strength error was 15.7 nAm in average and about 63 nAm at largest, which corresponds to 158% of the original current strength.

In Fig. 8 (two-dipole model), the location error was 3.7 mm in average and about 12 mm at largest, but the current strength error was 7.8 nAm in average and about 48 nAm at largest, which corresponds to 120% of the original current strength.

These errors in the above figures (Figs. 5-8; 40 nAm original dipole strength) together with the errors for the other four original dipole current strengths were averaged and summarized in Table 2.

4 Conclusions

When we employ the single-dipole model for estimating the two-dipole activity, the errors may be acceptable for the location and current orientation for some purposes, such as psychophysical experiments. However, the error in current strength (more than 50%) may not be acceptable.

References

1. B. Lütkenhöner, “Dipole separability in a neuromagnetic source analysis.” *IEEE Trans on BME.* **45**, 572–581, 1998.